AD-A106 659

TECHNICAL REPORT ARBRL-TR-02360

APPLICATION OF A HIGH POWER LASER TO DEMILITARIZATION PROBLEMS

Ona R. Lyman

September 1981

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

Approved for public release; distribution unlimited.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report ARBRL-TR-02360	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Application Of A High Power Laser To Demilitarization Problems		5. TYPE OF REPORT & PERIOD COVERED Final 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Ona R. Lyman		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Ballistic Research Laboratory (ATTM: DRDAR-BLT) Aberdeen Proving Ground, MD 21005		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1L161102AH43
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Armament Research & Development Command U.S. Army Ballistic Research Laboratory ATTN: DRDAR-BL , APG, MD 21005		12. REPORT DATE SEPTEMBER 1981 13. NUMBER OF PAGES 30
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Lasers, explosives, propellant, laser cutting, and laser drilling.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (ddg)

Attempts to experimentally cut rocket motors, puncture agent cavities, and perform other operations associated with demilitarization of munitions with a high power CO_2 laser are discussed. Laser requirements are outlined and problems associated with laser operations contiguous with hazardous materials are highlighted. It is concluded that while the use of a CO_2 laser of about 10 kilowatts output has advantages for some demilitarization operations, it is not practical for many.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. INTRODUCTION

The U.S. Army Toxic and Hazardous Materials Agency (ATHMA) has the responsibility for the development and demonstration of procedures and equipment for large scale demilitarization of obsolete or unserviceable chemical agents and munitions. Recently, a new munitions disposal system has been started up at Tooele Army Depot. As part of a continuing program, to study the application of developing technologies to the demilitarization task, the USAARRADCOM, Ballistic Research Laboratory (BRL) was asked to investigate the feasibility of using CO_2 lasers to section M-55 chemical rockets for demilitarization. Previous work had demonstrated that CO_2 lasers can be used effectively to cut chemical projectiles[1].

II. OBJECTIVE

Sectioning of the M-55 Rocket for demilitarization currently requires that six cuts be made at various locations on the rocket. The goal of these studies is to determine if a CO_2 laser can make these same cuts, and if so to specify the laser cutting parameters required.

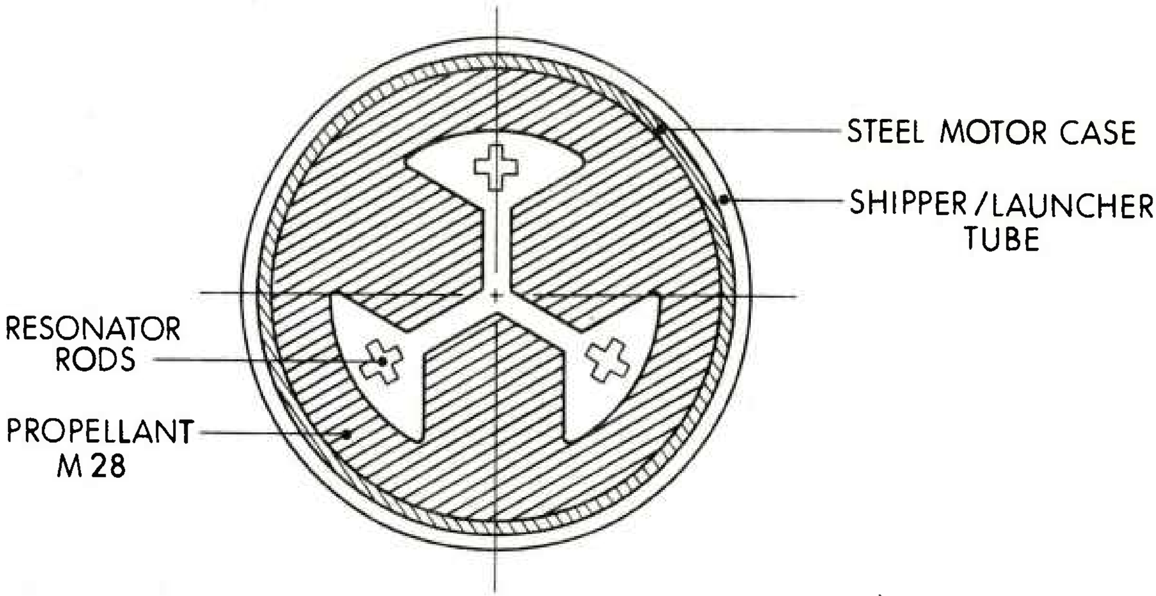
A. Rocket Description:

The M-55 Chemical Rocket is 115 millimeters in diameter by 1.96 meters long and is contained in a fiberglass shipper/launcher tube. The warhead is 0.59 meters long and is made of 6061 aluminum alloy with a wall thickness of 1.5 millimeters. The warhead contains a burster tube 0.49 meters long loaded with 1.45 kilograms of Composition B explosive. The agent cavity is approximately 90% filled with chemical agent. Aft of the warhead is the rocket motor section, 0.88 meter long. The motor case is 2.4 millimeters thick steel; and surrounds 8.71 kilograms of M28 propellant. Figure 1 shows the crossection of the rocket motor and lists the propellant composition. A point detonating M-417 fuse is attached to the nose of the rocket and a folded fin assembly is attached to the aft end. The entire rocket is contained in a fiberglass tube equipped with quick release end plugs. Demilitarization of this munition requires cutting the rocket in its shipping tube to eliminate handling operations.

B. Desired Cutting Opertions:

In the demilitarization of M-55 Rockets, the first operation is to puncture the agent cavity and drain the agent from the munition. Following this, the rocket is then cut into seven pieces as shown in Figure 2. The first cut is through the fuse and separates the burster explosive from the initiator components in the fuze. The second and third cuts divide the burster tube and warhead casing into two approximately equal parts for further processing. The fourth cut is through the rocket motor and yields a small portion of rocket motor with the black powder igniter and the metal parts connecting the motor section to the warhead. The sixth cut separates the fin assembly from the motor section while the fifth cut separates the motor into two nearly equal pieces. It is current practice to make these cuts simultaneously. No such restrictions are imposed on the attempts reported here to make similar cuts using a CO_2 laser. It is required, however, that the

[1] *Frank, K. and Roszak, R., Feasibility Experiments on the Demilitarization of Chemical Munitions by High Power Lasers, Part 1: Cutting Experiments, BRL MR 2756, June 1977.*



M28 PROPELLANT COMPOSITION

1.	NITROCELLULOSE	60 %
2.	NITROGLYCERIN	23.8 %
3.	TRIACETIN	9.9 %
4.	DIMETHYL STEARATE	2.6 %
5.	LEAD STEARATE	2.0 %
6.	2-NITRODIPHENYLAMINE	1.7%

Figure 1. Crossection of M-55 Rocket Motor

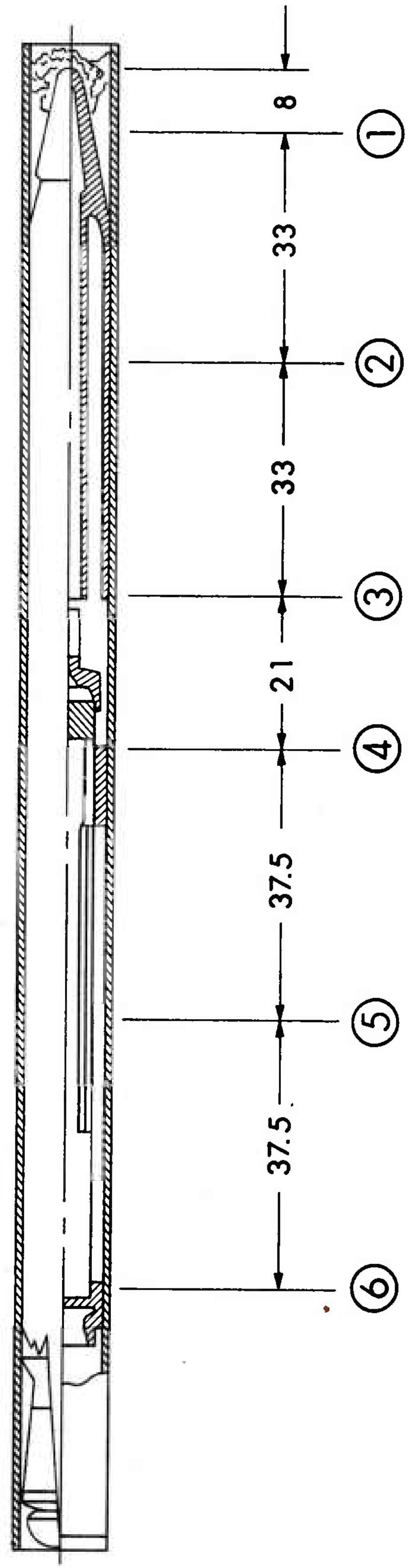


Figure 2. Locations for M-55 Rocket Cuts Spacing In Centimeters

cutting operations be performed with the fiberglass shipping tube in place. Furthermore, feasibility is not dependent on making the cuts at precisely the locations shown as long as the following conditions are met:

1. Fuse is separated from the burster.
2. Burster is cut into two nearly equal parts.
3. Motor is separated from the igniter.
4. Motor is cut into two nearly equal parts.

Demonstrated feasibility does require that the cuts can be reliably made through the motor and through the burster without igniting the propellant or explosive.

III. THE LASER AND FACILITY

The laser used in this feasibility study is the BRL 2 kilowatt CO_2 laser. It is an electric discharge laser with laser cavity, gas flow and electric discharge all coaxial. The premixed laser gas is recirculated by a vacuum blower with a few percent make up gas added during operation. For this program, a set of unstable resonator optics was installed as shown in Figure 3. This optical system delivers a maximum power output of 1500 watts, but the quality of the output beam is much improved over the hole coupled and top hat optical systems previously used. The output beam has an annular cross section as shown in Figure 4, a burn pattern obtained on a lucite block. The beam is nearly diffraction limited, and has an outer diameter of 57 millimeters and an inner diameter of 45 millimeters. Because of the explosives and propellant involved in these tests, the laser was set up in a concrete bomb proof building at the Spesutie Island test area. Figure 5 shows the outline of the building, barricades and experimental area. Laser access to the test area is provided by an 8 inch opening in the building wall and the barricades. The barricade provides protection to adjacent areas from accidental initiation of energetic materials and additionally shields these areas from scattered laser radiation. In order to accommodate the laser an 8'x12' addition was made to the original building and two interior walls were removed. The electrical service to the building was upgraded to 150 kilowatts. Completion of these modifications resulted in an excellent facility for studying laser reactions on energetic materials.

IV. APPROACH

In spite of the fact that it has been shown that explosives can be cut with CO_2 laser[2], at least in an unconfined configuration, the cutting of rocket motors and burster tubes was viewed as a task with the highest probability of failure. Failure is defined as ignition and burning of the propellant and/or explosive. Because it was believed that bare propellant

[2] *Harrach, R. J., "Estimates on the Ignition of High- Explosive by Laser Pulses," JAP Volume 47, No. 6, June 1976, p2473-2482.*

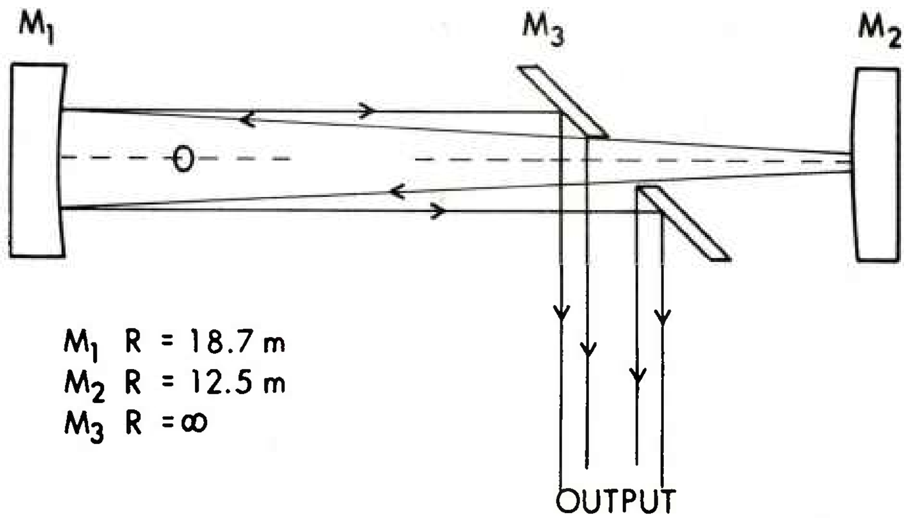


Figure 3. Unstable Resonator Optics for CO_2 Laser

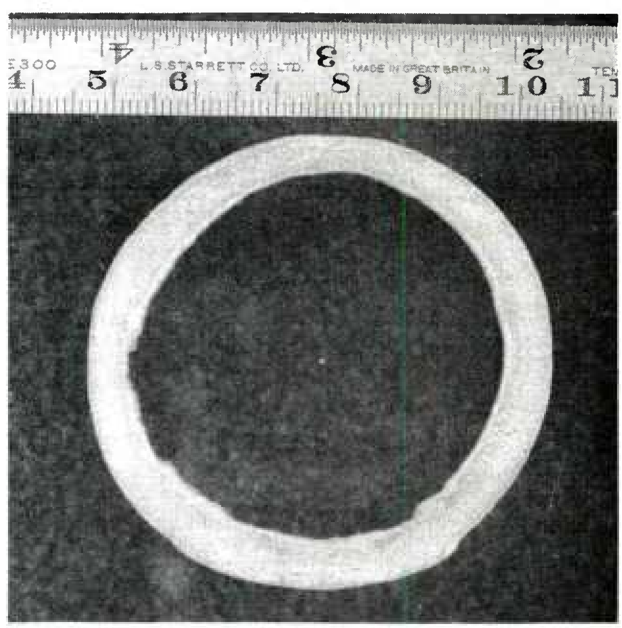


Figure 4. Laser Beam Crossection From A Lucite Burn Pattern

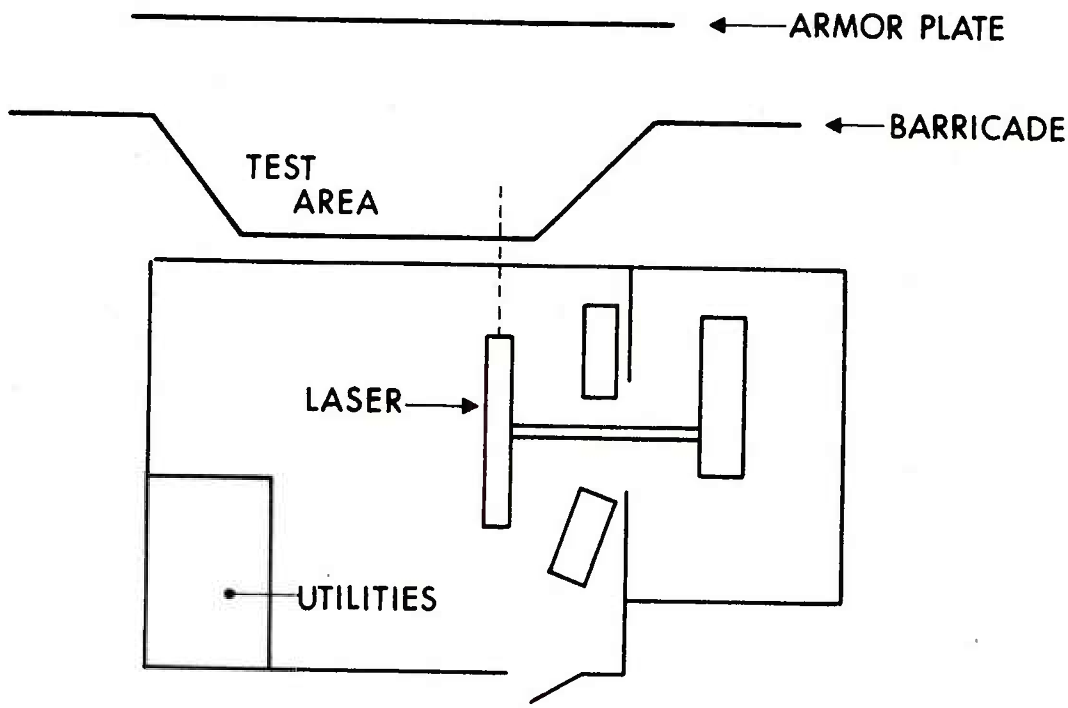


Figure 5. Outline Of Laser Test Facility

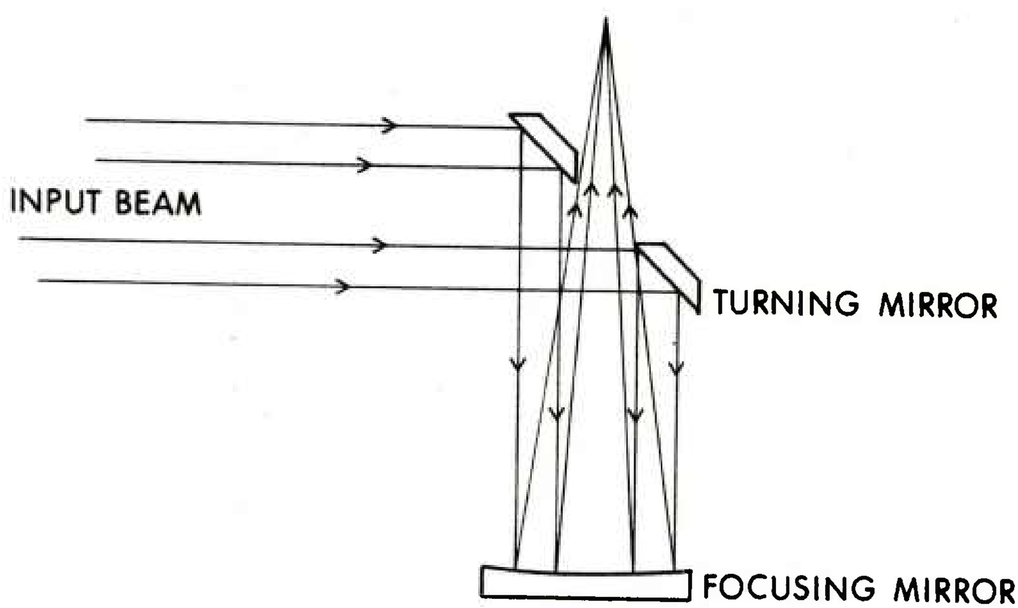


Figure 6. On Axis Focusing Optics for CO_2 Laser

cuts would be less likely to be ignited, the experimental plan was to progress from tests with small bare propellant samples to full diameter samples. These tests to be followed by cased propellant samples. Before we discuss that, however, it is worthwhile to look at the general laser cutting characteristics as they apply to these tasks with the laser to be used.

A. Laser Cutting Characteristics:

As was mentioned earlier, the modified BRL CO_2 laser has an annular output beam. There is an inherent advantage with this configuration for cutting operations. A rather simple system of mirrors allows the use of spherical focusing mirrors with the cutting spot (focal point) on the optical axis of the focusing mirror. Figure 6 shows a diagram of this arrangement. This system was built and used for some of the early test work. When propellant is cut there is a large amount of effluent generated. It was discovered that this effluent which tends to travel back up the beam was fouling the mirror surfaces. The use of air jets to deflect the flow of effluent was only partially effective, and the use of longer focal length mirrors resulted in an awkward system, which was difficult to align well. Furthermore, as we shall see using spherical mirrors off axis was not troublesome as long as angular misalignments are small. For these reasons, the optical configuration of Figure 6 was not used for these tests.

Because the laser cutting to be performed will be with spherical focusing mirrors used slightly off axis, it is useful to examine the focal spot sizes obtainable with practical mirror systems. For efficient cutting, it is desirable to work with the minimum focal spot obtainable. "The Handbook of Military Infrared Technology"[3] lists the following equations for minimum spot diameters, applicable to small angular misalignments of spherical mirrors.

1. Diffraction Limited Spot Diameter $B = 2.44\,\lambda\,(F/D)$

2. Spherical Aberration $B = 0.0078(F/D)^3$

3. Sagittal Comma $B = 0.0625\theta F(F/D)^2$

4. Astigmatism $B = 0.5\theta^2 F(F/D)$

B is the minimum obtainable diameter of the focal spot, λ, is the wavelength (10.6×10^{-6} meters), D is the beam diameter (.060 meters), F is the mirror focal length, and θ is the angle between a ray from the image spot to the mirror center and the normal to the mirror center. Figure 7 is a diagram looking down the laser beam axis showing the laser beam passing .070 meters above the rocket and then focused 0.150 meters to the right at the

[3] *Handbook of Miliary Infrared Technology, Chapter 10, p. 455, William Wolf Editor, 1965, Supt. of Documents, U.S. Government Printing Office, Wash., D.C. 20402.*

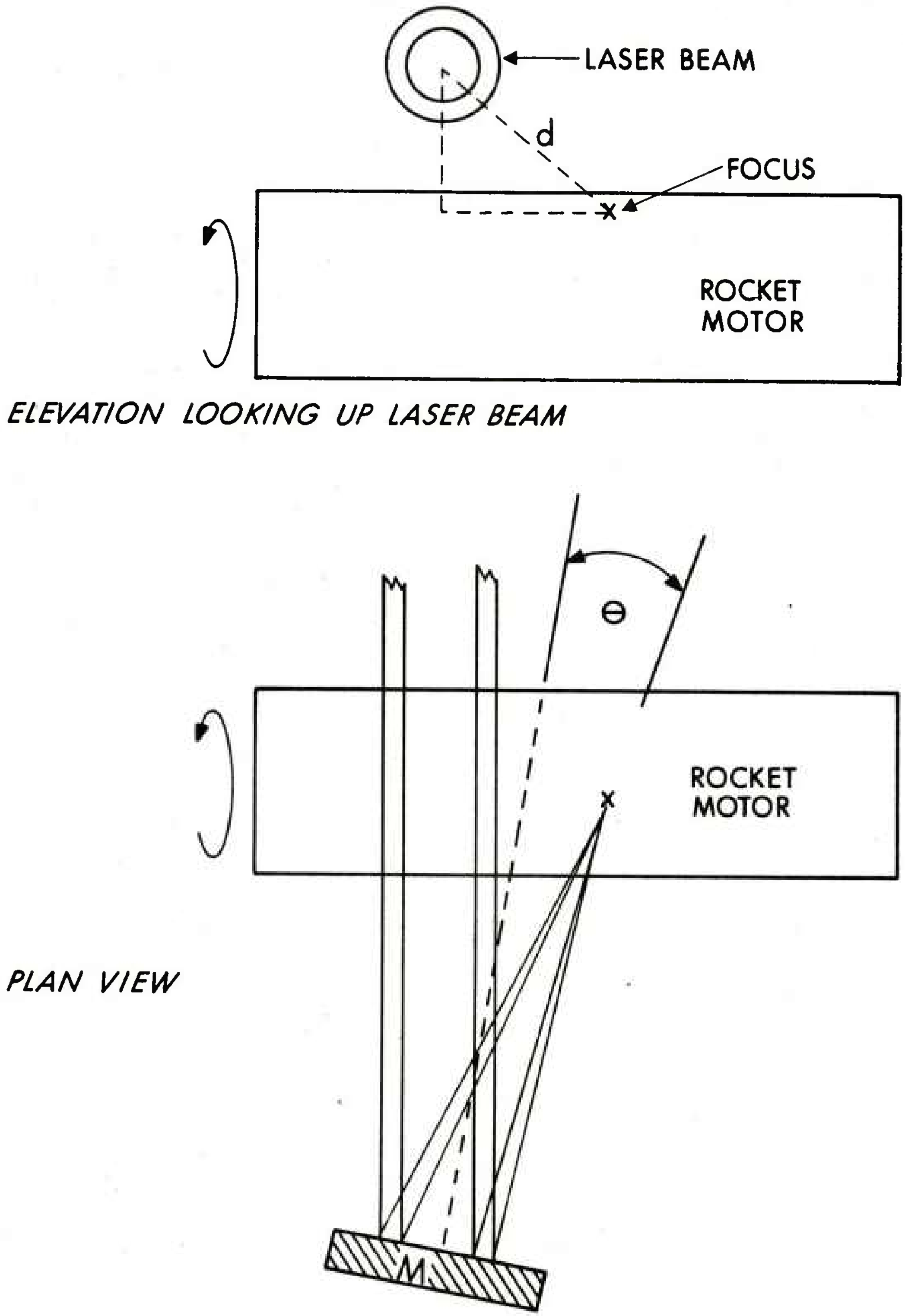


Figure 7. Cutting Geometry With Off Axis Focusing

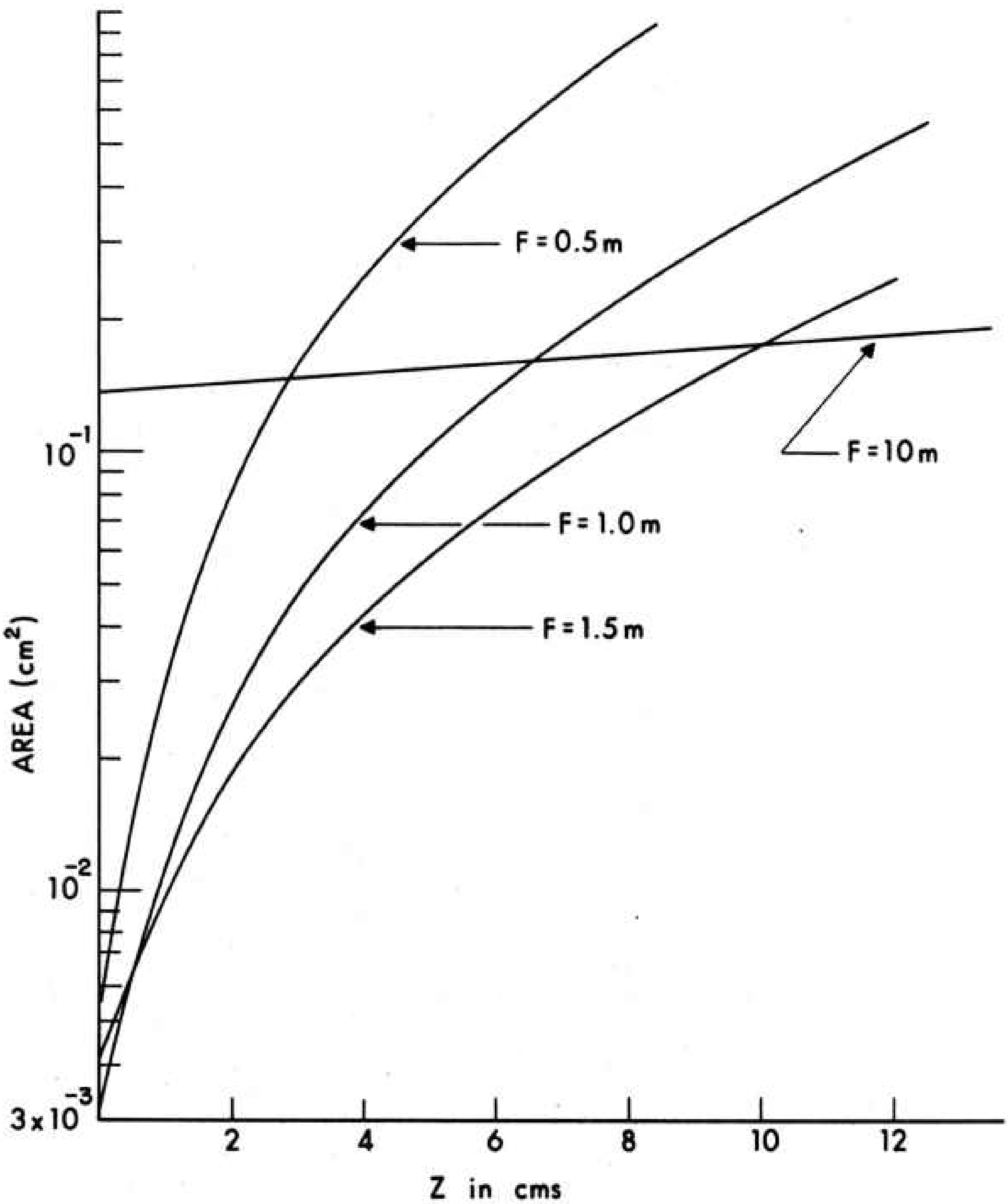


Figure 8. Focal Area As A Fuction of Distance z from Best Focus For 4 Different Focusing Mirrors

desired cutting line. The quantity $d/2F$ equals θ, in radians. It is assumed that the mirror is centered on the laser beam, and when performing experiments care must be taken to make certain such is the case.

Table I lists the diffraction limited spot diameter and the effect of off axis focusing for three focal length systems. It must be remembered that these represent minimum spot diameters for each contribution. For our case, because of the high quality of the laser output, the numbers are very good approximations of obtainable spot diameters. Reference 3 states, "The interaction of the various aberrations is, in general, difficult to predict precisely. For most purposes, however, it is sufficient to simply add the blurs and accept the sum as a good indication of the final image blur size."

TABLE I
FOCAL SPOT MINIMUM DIAMETERS FOR:
A. DIFFRACTION LIMITED SPOT
B. SPHERICAL ABERRATION
C. SAGITTAL COMA
D. ASTIGMATISM

F	F/D	θ	A	B	C	D
Meters		Radians		Millimeters		
0.5	8.06	.165	.208	.007	.079	.844
1.0	16.13	.083	.417	.002	.020	.227
1.5	24.19	.005	.626	.001	.009	.094

When we do this for our mirrors, we see that astigmatism is the most important contribution. We, also, note that astigmatism makes the 0.5 meters mirror of little value for laser cutting with our geometry. Furthermore, we see that for the experimental setup of Figure 7 a 1.5 meters focal length mirror should perform better than the 0.5 meter focal length mirror. For the mirrors listed in Table I, the one meter focal length mirror should yield the most intense focused beam, and the most efficient cutting. A one meter focal length mirror was used for nearly all the cutting experiments, the major exception being cutting tests on bare propellant samples, which will be discussed later.

Another aspect of laser cutting of material is the effect on the laser focused spot size caused by placing the surface to be cut at small distances from the focal point. A simple geometric analysis yields a good estimate of how the spot diameter varies as a function of Z, where Z is the distance from the focal point to the cutting surface. The following equation shows this relationship, and in Figure 8 curves of laser spot area as a function of Z for four focal length mirrors are plotted.

$$d = B + \frac{Z}{F}\left|D - B\right| \tag{1}$$

where,

d = diameter of laser spot

B = Best focus diameter of laser spot

D = Diameter of laser beam at focusing mirror

F = focal length of mirror

As can be seen in Figure 8, the positioning of the piece to be cut becomes less critical as the focal length of the system gets larger. In fact, for a 10 meter focal length mirror it is not critical at all. Unfortunately, the minimum spot area increases also with increasing focal length and because we are limited to outputs of about 1500 watts, long focal length systems are not practical for metal cutting with this laser.

A variety of treatments exist for calculating the cutting parameters for metal cutting with CO_2 lasers. Most are based on Carslaw and Jaegers's[4] "Conduction of Heat in Solids." The treatment we will follow is by W. W. Duley[5]. Duley considers a thin sheet lying in the x y plane moving with velocity v in the x direction. It is irradiated by a circular laser spot of Area πA^2 at the origin. The temperature T(x,y,t) can be approximated for point $r \neq 0$ by:

$$\exp\left(\frac{vx}{2\kappa}\right) = \frac{2\pi K l T_{xyt}}{\epsilon P f K_0 r v / 2\kappa} \tag{2}$$

P = incident power

ϵ = emissivity of metal sheet at laser wavelength

l = sheet thickness

K_0 = Bessel function of the second kind zero order

K = thermal conductivity

κ = thermal diffusivity

The assumption is made that the laser power absorbed over a finite area can be approximated by a point source at the origin. With the dimensionless generalized coordinates

---

[4] *Carslaw, H. S. and Jaeger, J. C., Conduction of Heat in Solids, 2nd Ed., 1959, Oxford University Press, London and New York.*

[5] *Duley, W. W., CO_2 Lasers and Applications, 1976, Academic Press, New York, Chapters 4 and 6.*

$$X = vx/2\kappa \qquad Y = vy/2\kappa \qquad R = vr/2\kappa$$

$$\text{and } C = \frac{2\pi K\, l\, T_m}{\epsilon P}$$

the location of the melting isotherm $T = T_m$ becomes,

$$\exp X = \frac{C}{f K_0 R} \tag{3}$$

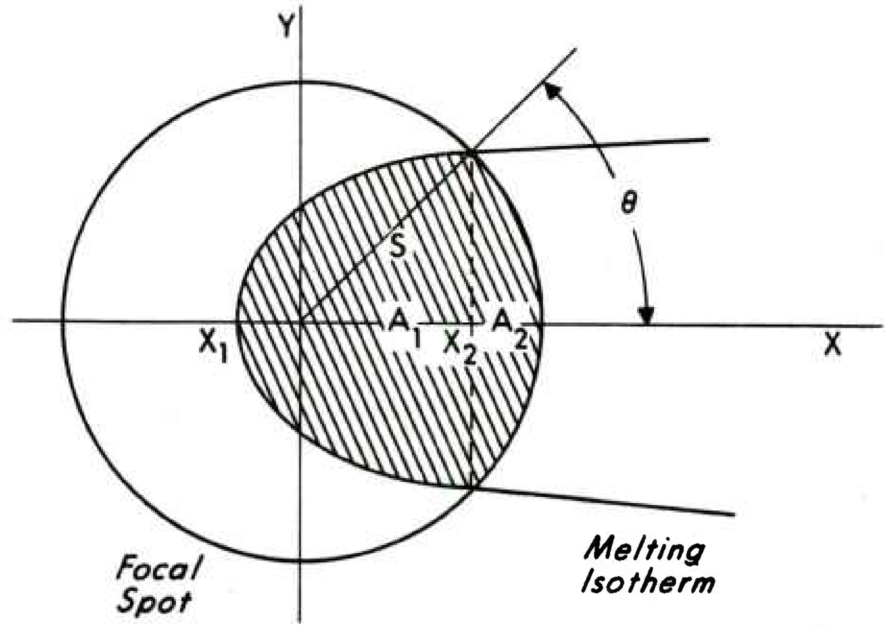
and, the laser spot radius becomes,

$$S = \nu A / 2\kappa. \tag{4}$$

It is further assumed that all the material within the melting isotherm is removed. The quantity f is the fraction of the total power ϵP that contributes to the heating of the solid material. Figure 9 shows two cases that must be considered in evaluating f. Figure 9a is the case where the maximum width of the isotherm lies outside the laser spot, and Figure 9b is where the isotherm maximum is inside the laser spot. The first case represents a cutting speed well below the critical cutting speed while the latter is close to the critical cutting speed. The critical cutting speed is the cutting rate where the molten material resolidifies before it is removed from the cut.

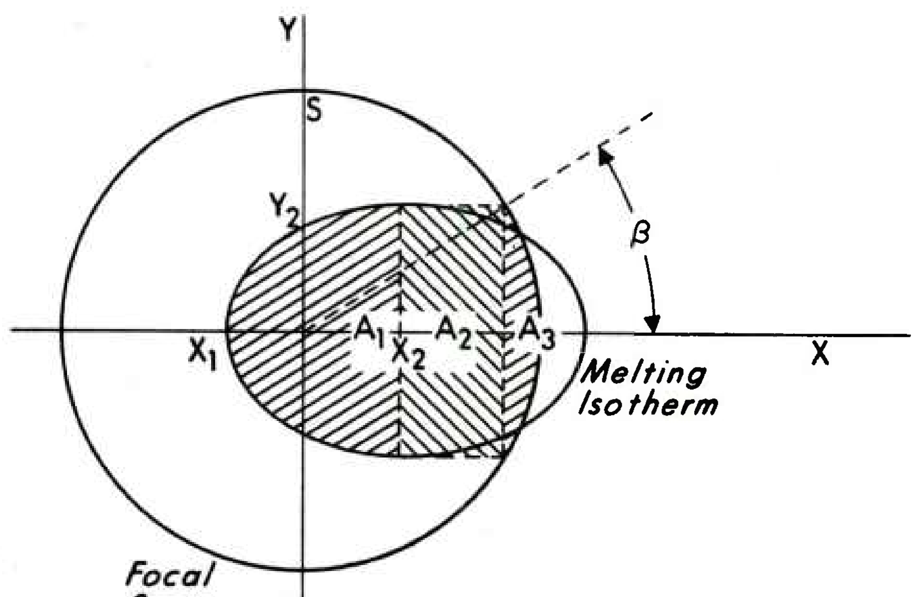
Duley has solved numerically for f as a function of S for a family of C values. These solutions are reproduced in Figure 10. Using these curves, we may now insert the material parameters and some desired cutting speeds to determine the laser power required. Duley cautions that one should use values f which are intermediate as the extremes may violate assumptions made in the derivation.

We should further note that the results should be conservative for our experiments because the model does not include the effects of the gas jet used to enhance cutting. The emissivity quoted in Table II is some average value, which may or may not be close to reality depending on the surface condition of material to be cut. The emissivity for aluminum given is rather high, but is justified on the basis that the fiberglass shipping tube which must be cut first will enhance absorption on the aluminum surface. The thermal properties of the materials are not constant with temperature, and intermediate values have been selected for calculations which at best will only be approximations. Table II lists the appropriate parameters.



9a.

Figure 9a. Focal Spot And Melting Isotherm, Cutting Speeds Below Critical Value



9b.

Figure 9b. Focal Spot And Melting Isotherm, Cutting Speeds Near Critical Value (Both a & b from Duley 6)

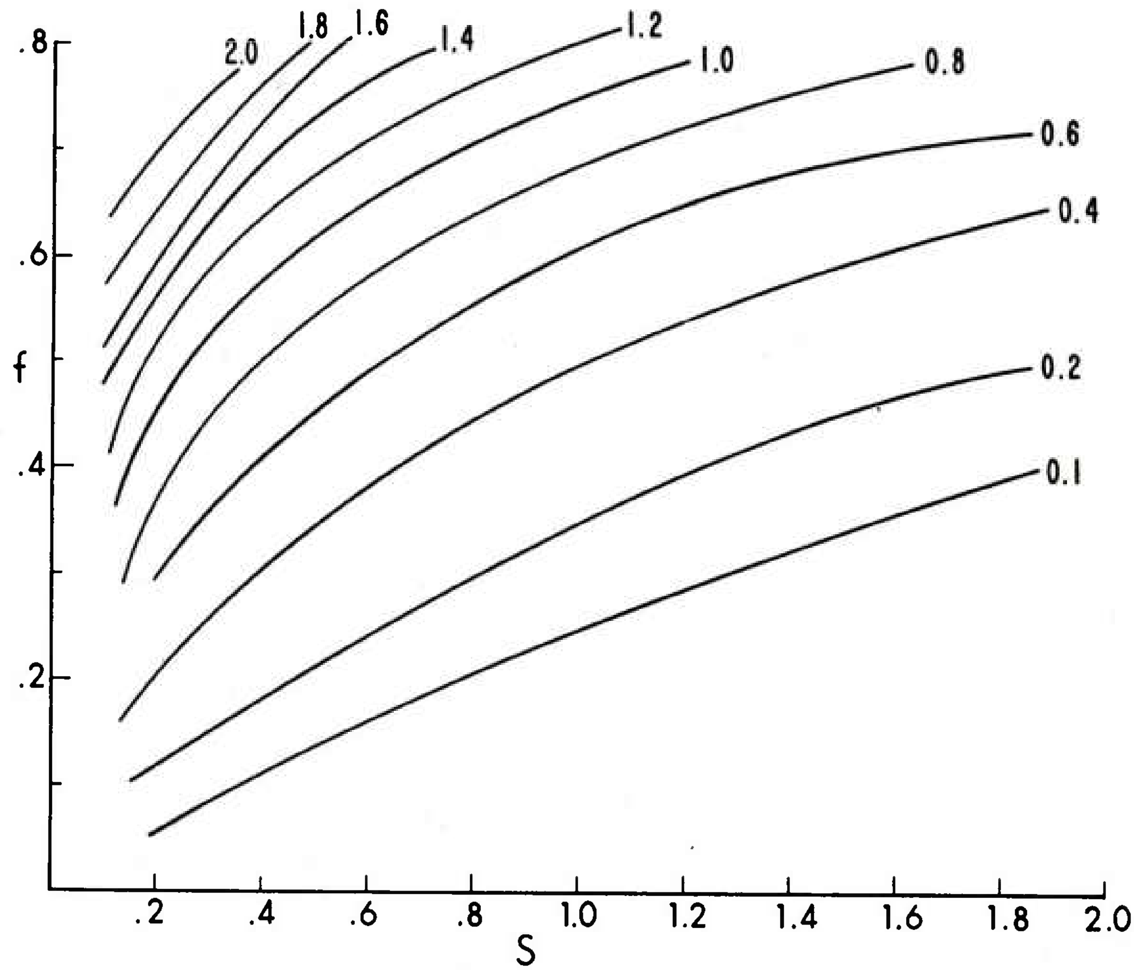


Figure 10. Theoretical Curves of f vs S for various C from Duley Reference 6

TABLE II

	Steel	Aluminum
P, Laser Power (Max) Watts	1500	1500
ϵ, Emissivity	0.9	0.6
l, Material Thickness cms	0.24	0.15
K, Thermal Conductivity Watts, $CM^{-1}\ {}^{o}C^{-1}$	0.5	2.2
κ = Thermal Diffusivity cm^2, sec^{-1}	0.14	0.8
T_m = Melting Temperature ^{o}C	1500	660
A = Laser Spot Radius cm	0.04	0.04

If for, example, we desire to cut the steel case at a cutting speed v = 5cm/sec, we can calculate the value of S.

$$S = vA/2K = .7 \tag{5}$$

Referring to Figure 10, we see that S = .7, C = .8 yields an intermediate value of f and should provide reasonably efficient cutting. The required power is then given by:

$$P = 2\pi K l T_m/\epsilon C \tag{6}$$

for C = .8 P = 400 watts

Using the same desired cutting rate for the aluminum warhead, we see that a power of 1020 watts is required. If our choice of emissivity is too large, we may have difficulty cutting the warhead section. For example, ϵ = .4 yields a power required of ~ 1500 watts.

The foregoing exercise indicates that, with the CO_2 laser available, we should have no trouble cutting the steel motor case, and that the aluminum warheads can also probably be cut although we have neglected the heat sink effect of the propellant in the motor and the ethylene glycol agent simulant in the warhead.

B. Rocket Motor Cutting Approach:

To successfully cut the rocket motor, it must be demonstrated that the shipping tube (fiberglass), motor case (steel), and propellant grain can be cut in one operation; i.e., without repositioning the motor, focusing mirror or gas jets. Changing the laser output, rotation speed of the motor, and laser spot location on the motor are permissible because they can all be easily done remotely. The cutting must be accomplished without igniting the propellant grain.

The experimental program planned to determine if cutting of rocket motors is feasible was as follows. As a first step, it will be determined if bare propellant grain can be cut with a laser without igniting the sample, and if so what the range of laser powers, rotation speed, gas flow and gas composition are required to reliably cut the full size propellant grain. Once the methods for successfully cutting the M-28 propellant grain have been established, the optimum cutting parameters for the motor case will be determined. If these parameters are outside the range for safe cutting of the propellant, we must then program the case cutting operation to cease upon completion of the cut reset the parameters for the propellant cutting and then cut the propellant. The laser operating procedures allow this to be easily done. The cutting of the fiberglass shipping tube is believed to present no problems, but final feasibility demonstrations must include cutting with the shipping tube in place.

C. Warhead Cutting Approach:

As we saw in Section A, the aluminum is more difficult to cut with the laser, and in the cutting estimates made, no account is taken of the effects of heat sinking by the agent simulant. However, because in the actual demilitarization the agent cavity is drained prior to cutting the munition, it will be permissible to make the cut on the warhead close to the top surface, where because of the ullage space in the warhead heat sinking effects will be minimal. Additionally, it is expected that cutting through the fiberglass shipping tube first will smoke up the aluminum surface and raise the value of the emissivity enough to allow laser cutting with minimal problems. Thus, no problems are anticipated in cutting the warhead, and in fact, it is probable that agent cavity puncture can be accomplished by a trepanning operation although the equipment to do this is not available.

V. RESULTS

In this section, the conditions required for successfully cutting, which were experimentally obtained, will be discussed.

A. Rocket Motor:

The cutting of bare propellant was thought to have a high probability of success, because of the work of Harrach. He demonstrated the when explosives were irradiated with flux density exceeding a critical value the explosive vaporized and was expelled away from the surface without igniting the solid explosive. The critical flux density depended upon the composition of the explosive. A similar phenomena occurs with the M-28 propellant. The critical flux density was not determined in these tests as it was a side issue to the feasibility study.

It was found that the propellant could be cut safely over a wide range of laser flux levels provided some simple conditions could be met. Because we wish to cut completely through the 110mm diameter grain, the grain was rotated during the cutting. Thus, it is necessary to penetrate to a depth of 55mm. Initial tests on small stationary pieces of propellant showed that, at hole depths greater than about 15mm, the probability of igniting the propellant increased until a probability of one was reached at about 25 millimeters.

The probability of ignition depended slightly on the hole diameter a larger diameter hole allowing deeper penetration before ignition. It is postulated that this is because the vaporized material from the bottom of a deep hole tends to react exothermally before it can escape from the hole generally resulting in ignition around the edge of the hole.

Because the propellant grain is being rotated during the cutting, a slot is cut into the grain around its circumference. The slot formed tends to allow the propellant material vaporized to escape more easily than is the case for the hole described above, and the probability of igniting the propellant at a given depth cut is reduced somewhat. Nevertheless, it was found to be necessary to use a jet of gas directed into the slot to prevent ignition for deep cuts. Helium, nitrogen and air were used with the gas jet. Helium gave the best results although nitrogen or air worked nearly as well and are suitable at intensities from 5000 to 15,000 watts cm^{-2}. For all gases, the jet was produced by flowing gas through 1/16" tubing with the nozzle placed within 1.0cm of the slot being cut and as close to the laser focal spot as physically possible. A gas pressure of 100 psig. was used for all the gases.

The speed of rotation of the propellant grain during cutting was varied to determine the effect of this parameter. It was determined that rotation at high speed was the most reliable. The maximum speed of rotation with the experimental set up available was 10 RPM. For a given laser intensity, the depth of cut per single rotation of the propellant grain decreases with increasing rotation rate. The total energy required to cut the grain remains constant within the parameter range available for experiment. The probability of ignition decreased with increased rotation rate and approached zero at a rate of 4.0 RPM, well below the maximum rotation rate available.

Because a relatively short focal length optical system was used (1 meter) a converging laser beam with a full angle of 3.5^{o} was obtained. The experimenter has the reasonable options of setting up the propellant grain to be cut with the best focus either on the surface of the grain or at the center of the grain. Intuitively, one might expect that, if the laser is focused on the propellant grain surface, the width of the cut would be narrowest there and might impede the escape of gases released deeper in the grain. If this is the case, then one would also expect the probability of ignition to be higher than it would be for a cut with the greatest width at the surface. Experimentally, it was shown that there was no significant difference in the cutting rate or in the probability of igniting the propellant regardless of whether the laser was focused at the surface of the propellant grain or at the center of the grain. Examination of partially cut grains showed that the width of the cut at the surface was from 2.5mm to 3.5mm regardless of the position of the focused spot. It is believed that for the case where the laser is focused at the surface the ejecta from the interior of the cut erodes the edges of the cut resulting in a cut width larger than the diameter of the focused spot.

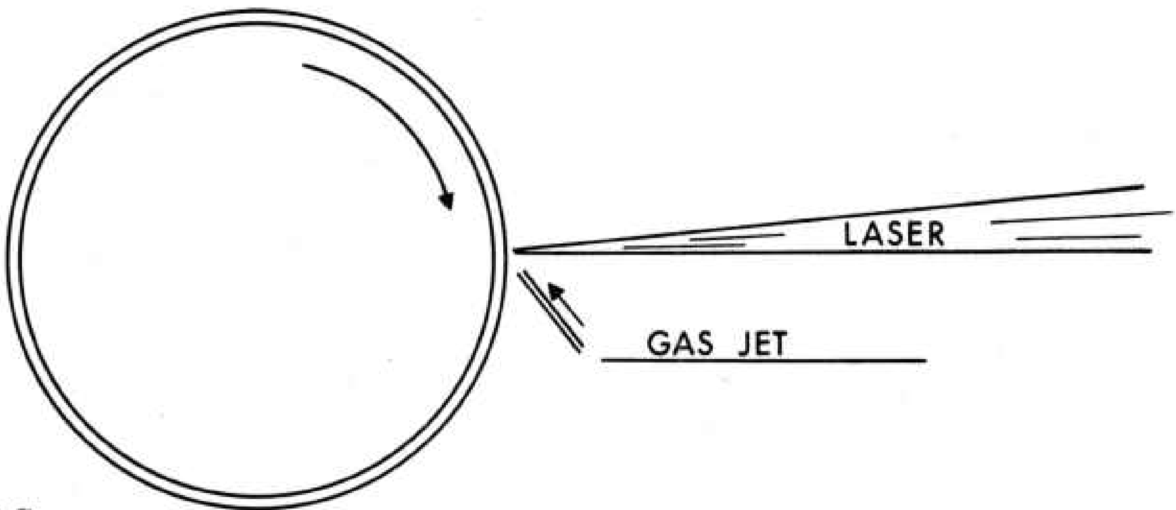
In summary, with regard to cutting the bare propellant grain, it can be said that it can be safely cut over a rather wide range of laser parameters provided one supplies a jet of gas to dilute and aid in removing the ejecta from deep cuts. Laser intensities used varied from $5x10^{3}$ watts cm^{-2} to $2x10^{4}$ watts cm^{-2}, lower intensities do not vaporized and remove material rapidly enough to prevent ignition while higher intensities tend to

produce cavities to deep to allow vaporized material to escape quickly, again leading to ignition.

The task of cutting cased propellant is much more difficult for two principle reasons. First, in order to cut steel efficiently with the 1.5kw CO_2 laser, it is necessary to aid the cutting with a jet of oxygen gas. As anyone who has observed oxygen assisted cutting of steel knows there is a large shower of sparks. These sparks can provide an ignition source if they lodge on the propellant surface. The second source of possible difficulty occurs because the cut through the steel case is less than 1.0mm wide and restricts the removal of propellant ejecta from the cut.

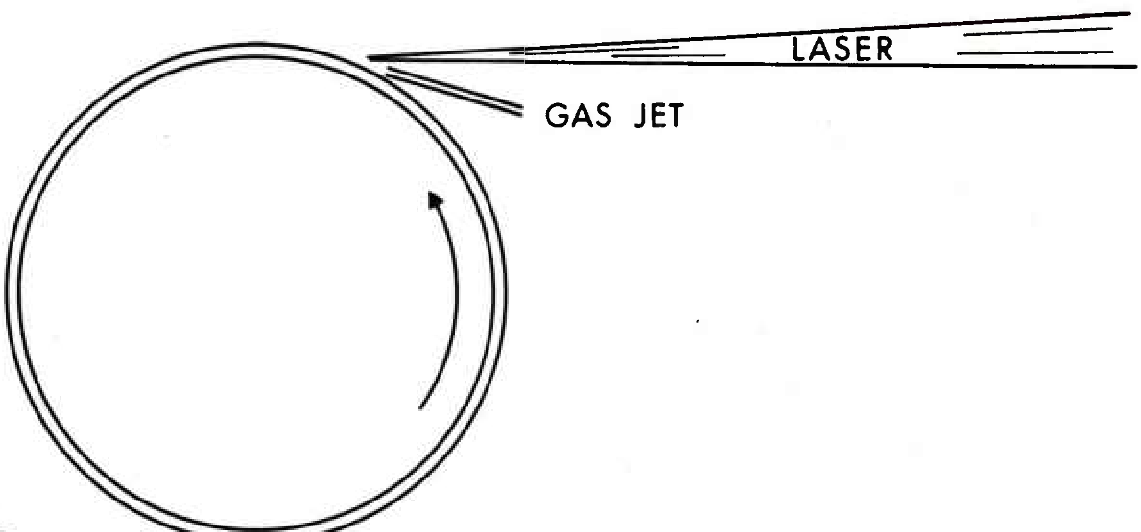
Initial experiments were made on empty motor case sections to determine how well the steel could be cut. The geometry of the experiment is shown in Figure 11a. This arrangement should yield the most efficient cutting, and with laser powers of 1500 to 1600 watts, it was possible to make a clean cut in 6.5 seconds. This is a linear cutting speed of approximately 5.5 cms per sec. When these cuts were made, it was observed that there was a large shower of sparks inside the case. It seemed likely that such an arrangement would have a very high probability of igniting the propellant grain. For this reason, a variety of other geometric arrangements of the laser beam and gas jet assist were examined. The combination that produced the least amount of debris inside the motor case is shown in Figure 11b. The orientation of the gas jet is more critical in this configuration, i.e. failure to cut all the way through the case or failure to remove the slag from the cut. An additional problem encountered with this orientation results if there is any wobble of the work piece. If the work piece moves downward a few millimeters, the laser beam will miss the work piece; if it moves upward the laser beam will strike the work piece at a point inside the best focus, a condition which can change the laser intensity by a factor of as much as 30. The glass blowing lathe, which was being used was tested and adjusted to run true within $\pm$ 0.5 millimeters. Although cutting problems were experienced prior to truing the lathe rotation, this should not present any problems to the designer of a laser cutting system. Cutting speed with this arrangement of gas jet and beam is reduced by about a factor of 10 to a linear cutting rate of 6.0mm per sec. The slower cutting rate results in a higher temperature in the motor case on either side of the cut. This gives an additional potential source of ignition.

Six test cuts were made using the configuration of Figure 11b with a section of propellant grain in the motor case. In all six trials, the propellant ignited within 15 seconds. Observation by closed circuit television indicated that ignition was occurring at a spot about 1 to 2cms along the cut from the spot irradiated by the laser. It was, also, noted that the motor case was red hot around the cut for a like distance. To overcome this problem, an aspirator spray was installed which blew a water mist directly on the cut as close to the cutting point as was physically possible (approximately 0.6 to 1.0 cms). Another series of test cuts were made using the water spray. For this series, again ignition occurred in all tests, but the time of ignition was increased to times ranging from 30 to 50 seconds after starting the cut. The motor case no longer was hot enough to emit any visible radiation indicating that the water spray was helping to keep the case cool. It was impossible to determine where along the cut ignition was occurring, but it did appear that ignition was not confined to a specific spot.



11 a.

Figure 11a. Most Efficient Cutting Configuration For Empty Motor Case



11 b.

Figure 11b. Configuration Used When Propellant Is In Motor Case

Oxygen gas is required to make the cut in the motor case with the cutting geometry used and the laser power available. Excess oxygen may aid in the ignition of the propellant and it was decided based on our experience with bare propellant to add 4 helium jets around the circumference of the motor case to blow into the cut. These gas jets should help to keep the debris out of the cut as well as diluting and cooling any oxygen and combustion products remaining in the cut. It had been noted earlier when cutting the empty motor cases with this cutting set up that the sparks and molten particles that came inside the case followed a path around the inside circumference. The helium gas jets should help to remove this material. The first test tried with this setup was a success. The steel motor case was cut without igniting the propellant. The propellant was subsequently cut by moving the laser spot down to the motor axis and reducing the laser power. The time required to cut the motor case was 60 seconds. A series of 10 tests under identical conditions was then attempted. Ignition occurred in all ten tests, the time of ignition varied from 45 seconds to 62 seconds.

Because success appeared so near (ignition occurred in some cases after the cut was completed), a series of tests were initiated with minor variations of the gas jet angle of attack. Observation during these tests was centered on trying to determine where ignition was occurring. In forty more tests, only in two cases was the motor case cut without igniting the propellant. It appeared that ignition was occurring between the motor case and the propellant grain. Post cut examination of the propellant grain for the three successful cuts tends to reenforce this observation, as in each case there were one or more areas on the side of the propellant grain where ignition had started and then been quenched. Figure 12 shows one of the successful cuts of the motor case. There is evidence here that the propellant adjacent to the cut has started to react and then extinguished. It is postulated that hot steel particles lodging between the propellant and motor case are the source of ignition. If the conditions are right, ignition of the propellant can occur. Because we experienced only 3 successes in 50 trials, it is apparent the conditions for ignition are most often right. A series of tests was also performed with the motor case rotated about a vertical axis with no change in the results.

As a result of the above experiments, we must conclude that the cutting of M-55 rocket motors with the BRL laser is not a practical procedure. There are conditions outside the range of capabilities for these tests, which may possibly have a chance of success. The most likely of these is the use of a higher power laser. If a higher power laser was used for the cutting of the steel case, then one could use an inert gas jet to remove the melted steel. This avoids the exothermic oxygen steel reaction occurring in tests reported here. It probably does not avoid blowing hot molten steel into the crevice between the motor case and propellant grain.

B. Warhead:

The warhead on the M-60 rocket, which is a training round for the M-55, is filled with ethylene glycol to simulate the agent. Test cuts were made using both the experimental set ups shown in Figure 11. For the set up shown in Figure 11a, cuts could be made with a laser output of 1600 watts. Some difficulty was experienced in starting the cut, but once started a linear cutting speed of 2 - 3 cms. per sec could be maintained. Tests using the

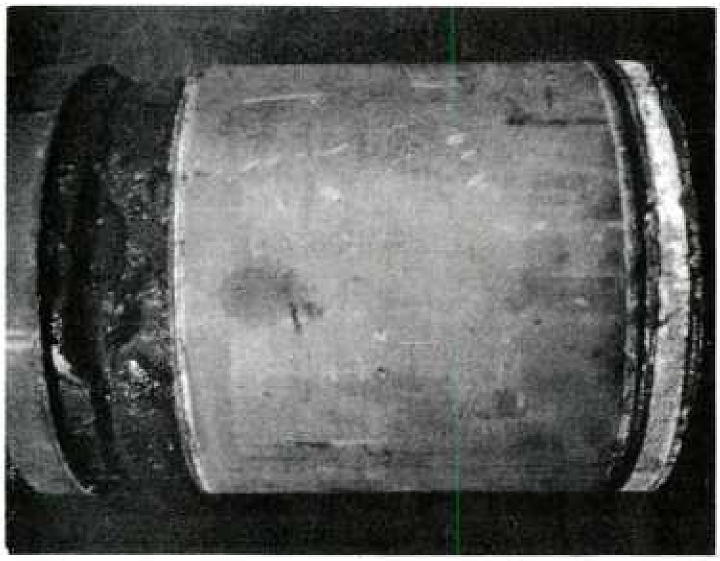


Figure 12. Photograph of Propellant Grain Showing Where Ignition Between Propellant and Case Occured, But Did Not Propagate

near tangential laser beam of Figure 11b were completely unsuccessful. This is a result of the high reflectivity of the aluminum warhead. A laser with higher power would cut the warhead rather easily especially after the initial penetration. Because in the final configuration, it is desirable to cut the rocket in its shipper/launcher tube a series of test cuts were made with this tube in place. It was found for these cuts that an air jet was better than an oxygen jet, giving a much cleaner cut with less charring around the edges of the cut. As was anticipated, the coupling of laser energy to the aluminum increased as a result of smoking the aluminum by cutting the fiberglass tube first. With this configuration; i.e., aluminum warhead surrounded by a fiberglass tube, it was possible to cut the warhead at a linear rate of 4 cms per second. The cutting rate was nearly the same regardless of whether the incident beam attack was along a radius or tangential to the warhead. The cooling effect of the ethylene glycol agent simulant did not alter the cutting rate significantly at the power levels used in these tests, (1500 watts).

C. Agent Cavity Puncture:

As mentioned earlier, agent cavity puncture is an important operation in demilitarization of chemical munitions. The cuts made in the warhead discussed in the previous section were approximately 0.5mm wide. Such a narrow kerf is unsuitable for draining the agent as too much time is required. It is recommended that for agent cavity puncture a trepanning type cut be made in the agent cavity. The necessary equipment to perform this type of cut was not available for testing, but generally is available at a laser metal working facility. On the basis of numbers obtained in warhead cutting tests, a 2 cm diameter hole could be cut into the warhead in approximately 2.0 seconds, with shipper/launcher tube in place.

VI. RECOMMENDATIONS

Because of our inability to cut the cased propellant without igniting it, the use of lasers for processing M-55 rockets for demilitarization is not an attractive approach. The primary cause of ignition, which we were unable to control, is from hot steel particles penetrating the space between the propellant and the case. If the propellant had been bonded to the case, it is the author's opinion that the rocket motor could have been successfully cut. The laser did perform well on the tasks of cutting the warhead section and puncturing the agent cavity. Previously reported work reference 1, in conjunction with the experiments reported here, indicate that the CO_2 laser, as a metal working tool may have application in the demilitarization of chemical munitions. In particular, agent cavity puncture appears to be a task a to which the laser is particularly well suited. Its principle advantage over mechanical methods is that it exerts no mechanical force on the munition. This means that no special clamping devices are required. For cylindrical munitions, a simple vee block would suffice. This could be a significant advantage where only small quantities of a munition need to be demilitarized, or where, if a portable laser is available, munitions need to be demilitarized "in insitu". An evaluation of the efficiency and cost effectiveness of a laser for specific demilitarization operations is beyond the scope of the program reported here, however, a commercially available metal working laser with an output of from 5 to 10 kilowatts would be adequate for any of the required demilitarization tasks.

VII. ADDENDUM

After completion of the major thrust, of the feasibility study a few brief tests were made, at the request of the ATHMA group. Each test was related to previous laser demilitarization studies and addressed a very specific question.

A. Burster Burnout:

The first task was to measure the pressure rise and agent simulant temperature rise in a sealed agent cavity while the burster tube explosive was burned out. This simulates a problem encountered when burning out a burster tube stuck in a warhead. A stimulated agent cavity was fabricated from a section of M-60 rocket motor case 115mm in diameter and 500mm long. A thick wall burster tube holder was mounted on the axis. Thermocouples were placed within 5mm of the burster tube in the agent simulant near both ends and at the midpoint of the burster tube. Ethylene glycol was used as the agent simulant and filled 90% of the available volume. An M-54 burster tube 17mm inside diameter was filled with composition B sealed at one end and inserted in the holder.

The initial test was to be an unassisted burnout of the explosive. The explosive was initiated by a 2 second burn of a 300 watt laser beam. After burning for 6.5 minutes, the explosive fire self extinquished. The laser was turned back on and the explosive burned for another 6 to 7 minutes before it extinquished again. Laser power was increased to 500 watts and burning continued for another 7 minutes. The maximum temperature increase was 17^{o}C at the top thermocouple. The system was mounted vertically and initiated at the top. The other two thermocouples showed increases of less than 10^{o}C. No increase in pressure was recorded. The sensitivity of the pressure gauge was 2 psi.

Post test examination showed the burster tube to contain a lot of charred material. Also, it was discovered that there was 75 millimeters of unburned explosive in the bottom of the tube. It is postulated that the charred material prevents the laser beam from penetrating to the bottom of the tube. If the system had been inverted, it is likely that the molten explosive would have run out the burster tube and burned externally. This configuration was not tested.

A second test was made this time with a 1300 watt laser assist. Under these conditions, it was possible to burn out all the explosive in approximately 2 minutes. Again, there was no measurable rise in the pressure. The top thermocouple recorded a 25^{o}C temperature increase while the bottom and midpoint thermocouples recorded less than 5^{o}C and 10^{o}C

increases respectively. It appears from this limited test data that burster tube burnout of intact warheads can be accomplished with only a small temperature rise in the agent.

A few tests were performed to determine the effect of laser assistance in burning explosive from burster tubes. As in the previous tests the tubes were mounted vertically to prevent molten explosive from flowing from the tube. The burn time for a composition B filled M-54 burster tube 17 millimeters inside diameter, was 38 minutes with no laser assist. This burster tube is about 51 cms long. After burning the tube contains a large quantity of charred material. Tests with 750, 1050 and 1400 watts of laser power delivered to a 0.38 cms^2 area reduced the burn times to 15 minutes, 7 minutes and 5.5 minutes respectively. After burnout the burster tubes had large amounts of charred material inside. Additional tests with M-54 burster tubes cut to 26 cms and 13 cms long were performed. With no laser assist burn times of 12 minutes and 4 minutes were recorded. The laser assisted burns with power levels comparable to those used for the long tubes showed only slight dependence on the laser power. The 26 cm tubes took slightly longer to burn, 2.5 minutes to 1.5 minutes, then the 13 cm tubes which took 2 minutes to 1 minute. The longer time in each case corresponding to lower laser power. Although laser burnout of burster tube explosive requires less time than non-laser assisted burnout other techniques would appear to be more practical and efficient for removing explosive from burster tubes.

B. <u>Weathered Metal Cutting:</u>

A brief series of laser cuts were made on 3.0 millimeter thick steel plates . Some plates were rusty while others were covered with dried mud up up to 5 millimeters thick. These tests were to simulate conditions occurring where munitions to be demilitarized many have been buried for a long period. As expected, this treatment did not effect the cutting rate. In general, initial puncture was somewhat easier probably due to increased laser coupling efficiency. For the samples with thick layers of mud, the laser heating and oxygen gas jet quickly exposed the metal surface, and cutting proceeded in a normal manner.

C. <u>Cutting Immersed Motor Cases:</u>

A series of five attempts were made to cut rocket motors with the laser while the motor was 90% immersed in water. A small tank was fabricated to contain water around the area to be cut and still allow the motor case to be rotated. A 5.0 centimeter section of propellant was fixed in the motor case where the cut was to be made. The ends of the motor case were sealed to keep out all water, except that which could enter through the laser cut. The laser beam - motor case configuration was the same as shown in Figure 11b. The motor case extended slightly above the water surface with an exposed arc length on the motor surface of approximately 2 cms. The steel motor case was easily cut using an oxygen gas jet assist. As was the case in earlier experiments, the propellant sample was ignited and totally consumed in all five trials.

DISTRIBUTION LIST

No. of Copies	Organization
12	Commander Defense Technical Info Center ATTN: DDC-DDA Cameron Station Alexandria, VA 22314
1	Commander US Army Ballistic Missile Defense Advanced Technology Center ATTN: Dr. David C. Sayles P. O. Box 1500 Huntsville, AL 35807
1	Commander US Army Materiel Development and Readiness Command ATTN: DRCDMD-ST 5001 Eisenhower Avenue Alexandria, VA 22333
1	Commander US Army Materiel Development and Readiness Command ATTN: DRCDE-DW, Mr. S.R. Matos 5001 Eisenhower Avenue Alexandria, VA 22333
4	Commander US Army Armament Research and Development Command ATTN: DRDAR-TSS (2 cys) DRDAR-LCE, Dr. R.F.Walker DRDAR-LCE, Dr. N. Slagg Dover, NJ 07801
1	Director US Army ARRADCOM Benet Weapons Laboratory ATTN: DRDAR-LCB-TL Watervliet, NY 12189
1	Commander US Army Armament Materiel Readiness Command ATTN: DRSAR-LEP-L, Tech Lib Rock Island, IL 61299
1	Commander US Army Aviation Research and Development Command ATTN: DRDAV-E 4300 Goodfellow Boulevard St. Louis, MO 63120
1	Director US Army Air Mobility Research and Development Laboratory Ames Research Center Moffett Field, CA 94035
1	Commander US Army Communications Rsch and Development Command ATTN: DRDCO-PPA-SA Fort Monmouth, NJ 07703
1	Commander US Army Electronics Research and Development Command Technical Support Activity ATTN: DELSD-L Fort Monmouth, NJ 07703
1	Commander US Army Missile Command ATTN: DRSMI-R Redstone Arsenal, AL 35809
1	Commander US Army Missile Command ATTN: DRSMI-YDL Redstone Arsenal, AL 35809
1	Commander US Army Missile Command ATTN: DRSMI-RK, Dr. R.G. Rhoades Redstone Arsenal, AL 35809
1	Commander US Army Tank Automotive Research and Development Command ATTN: DRDTA-UL Warren, MI 48090

DISTRIBUTION LIST

No. of Copies	Organization
1	Director US Army TRADOC Systems Analysis Activity ATTN: ATAA-SL, Tech Lib White Sands Missile Range NM 88002
1	Commander US Army Research Office ATTN: Chemistry Division P. O. Box 12211 Research Triangle Park, NC 27709
1	Commander Office of Naval Research ATTN: Dr. J. Enig, Code 200B Arlington, VA 22217
1	Commander Naval Sea Systems Command ATTN: Mr. R. Beauregard, SEA 04JE Washington, DC 20362
1	Commander Naval Surface Weapons Center ATTN: Code G13 Dahlgren, VA 22448
2	Commander Naval Surface Weapons Center ATTN: Mr. L. Roslund, Code R122 Mr. M. Stosz, Code R121 Silver Spring, MD 20910
3	Commander Naval Weapons Center ATTN: Dr. L. Smith, Code 3205 Dr. A. Amster, Code 385 Dr. R. Reed, Jr., Code 388 China Lake, CA 93555
1	Commander Naval Explosive Ordnance Disposal Facility ATTN: Technical Library, Code 604 Indian Head, MD 20640

No. of Copies	Organization
1	Commander Naval Research Laboratory ATTN: Code 6100 Washington, DC 20375
1	Commanding General Fleet Marine Force, Atlantic ATTN: G-4 (NSAP) Norfolk, VA 23511
1	AFRPL/MKPA (Mr. R. Geisler) Edwards AFB, CA 93523
1	Director Lawrence Livermore Laboratory University of California ATTN: Dr. M. Finger Livermore, CA 94550
1	Director Los Alamos Scientific Lab ATTN: Dr. B. Craig, M Division P. O. Box 1663 Los Alamos, NM 87545
1	Schlumberger Well Services ATTN: Dr. C. Aseltine 5000 Gulf Freeway Houston, TX 77023

Aberdeen Proving Ground

Dir, USAMSAA
ATTN: DRXSY-D
DRXSY-MP, H. Cohen
Cdr, USATECOM
ATTN: DRSTE-TO-F
Dir, USACSL, Bldg. E3516, EA
ATTN: DRDAR-CLB-PA
Cdr, USA Toxic & Hazardous
Materials Agency
ATTN: DRXTH-EF (4 cys)
DRXTH-TE-D, E. Coale
(12 cys)

USER EVALUATION OF REPORT

Please take a few minutes to answer the questions below; tear out this sheet, fold as indicated, staple or tape closed, and place in the mail. Your comments will provide us with information for improving future reports.

1. BRL Report Number ______________________________

2. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which report will be used.)

____

____

____

3. How, specifically, is the report being used? (Information source, design data or procedure, management procedure, source of ideas, etc.) ______________________________

____

____

4. Has the information in this report led to any quantitative savings as far as man-hours/contract dollars saved, operating costs avoided, efficiencies achieved, etc.? If so, please elaborate.

____

____

5. General Comments (Indicate what you think should be changed to make this report and future reports of this type more responsive to your needs, more usable, improve readability, etc.) ______________

____

____

____

6. If you would like to be contacted by the personnel who prepared this report to raise specific questions or discuss the topic, please fill in the following information.

Name: ______________________________

Telephone Number: ______________________________

Organization Address: ______________________________

____

____